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Published in:
Energy and Buildings

DOI:
[10.1016/j.enbuild.2012.12.008](https://doi.org/10.1016/j.enbuild.2012.12.008)

Publication date:
2013

Document Version
Author accepted manuscript

[Link to publication in ResearchOnline](#)

Citation for published version (Harvard):
Emmanuel, R, Kumar, B, Roderick, Y & McEwan, D 2013, 'A universal climate-based energy and thermal expectation index: initial development and tests', *Energy and Buildings*, vol. 58, pp. 208-218.
<https://doi.org/10.1016/j.enbuild.2012.12.008>

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A universal climate-based energy and thermal expectation index: Initial development and tests

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Abstract

We prototyped a set of energy indices that can be used to assess, classify and compare any worldwide climate (weather data or extrapolated climate change data) to understand its energy burden on buildings and for the use in sustainable building design. The indices are intended as rapid and interactive holistic design tools applicable to any building type, with any design strategy, in any location worldwide and for the simple quantification of the impact of climate change on building energy use over its lifecycle. The indices are based on the fact that climate underlies building energy use and it is therefore possible to compare designs relative to climate, visualize where design emphasis needs to be placed and directly and interactively track the effect of design strategies.

We then test them against the well-known Mahoney's Table as well as against other parametric simulation software to evaluate their robustness and applicability in a wide variety of climatic contexts from around the world. The index works well in most climates except hot, humid ones. Lessons for future development and implementation are discussed.

Key words

Climate Energy Index, Building Energy Index, building simulation, IES-Virtual Environment

1. Introduction

Buildings are designed to create a suitable internal environment for human comfort. The successful design of comfortable buildings relies on an appropriate understanding of the climate. Climate underlies building energy use, therefore a climate-responsive building design is the key to achieve a comfortable yet energy efficient building environment. However, in practice, it is difficult to translate climate data into meaningful information that can capture the local climatic characteristics. There have been numerous attempts to establish a relationship between comfort, climate and built form and to explore various climatic design strategies. These approaches are limited in a variety of ways such as to certain building types or climate types. In addition, these approaches are still relatively complex and require either a high level of interpretation to be correctly utilised in the design process or vast amounts of data to be of practical use.

In order to overcome these difficulties a set of globally applicable energy indices have been developed by the Integrated Environmental Systems Ltd (IES) – makers of the dynamic thermal simulation software IES Virtual Environment (IES VE). The indices – Climate Energy Index (CEI) and Building Energy Index (BEI) – are interactive holistic design tools to assess, clarify and compare any worldwide climate data and hence to quantify the climate impact on building energy performance.

The Climate Energy Index (CEI) provides an indication of the consequence or 'energy burden' of climate with respect to building performance at an accepted standard of comfort at a particular geographic location. It represents an annual sum of energy required to condition 1m^3 of air at any weather hourly ordinate to the nearest boundary of a human comfort zone. The human comfort zone is determined based on ISO 7730 occupant comfort standard using Predicted Mean Vote (PMV). Although there are other approaches to thermal comfort ISO 7730 represents the most widely used comfort standard around the world. The Building Energy Index (BEI) is an overall performance indicator for building design strategy. It comprises the climate related and climate

unrelated energy loads. The BEI can be compared directly with simulated or measured energy consumption data of a proposed building to benchmark its energy performance.

In this paper we present these indices and perform validity and robustness tests by comparing the indices against well-known previous works as well as simulated building energy consumption data for 10 different buildings in 14 different geographic locations around the world. Implications for future development and work are explored.

2. Background

2.1 History of energy indices for buildings

Efforts to quantify normative energy consumption in buildings (especially housing) began with the energy crisis in the 1970s. Given the wide disparity in energy consumption patterns even within the developed world and the importance of the built environment in reducing national energy consumption, there was a need to benchmark building energy performance with a view to standardize and codify the best practices. Such indices are usually expressed in normalised energy units (such as kWh/m²)[1]. A review of early attempts to develop energy indices is given by Yannas [2].

One of the early 'energy indices' was developed by Yannas [3]. According to this index (called the Energy Index – EI), a notional detached dwelling complying with the 1990 UK Building regulations would consume approximately 100-115 kWh per annum per m² of floor area. A building fulfilling all the known 'good design' principles (i.e. south facing windows, double glazing, insulated walls and roofs, tight construction – 0.5 Air Changes per hour [ACH] and mechanical ventilation with heat recovery) will have an EI of less than 30 kWh/year/m² [4]. This compares well with the most stringent current standards (for example the Passivhaus standards [5] – 15 kWh/year/m² or the UK Code for Sustainable Homes [6] – 45 kWh/year/m²).

Attempts to quantify the 'climate burden' imposed by external climate on buildings have an even longer history. Early attempts from the time of Silpasatra in India [7] and Vitruvius [8] in Rome focused on intuitively developed design exemplars based on climate types. An early approach based on meteorological data was first attempted by Mahoney in 1965 [9]. We will return to this method later in the analysis.

2.2 Recent developments in building/climate indices

The consumption of energy in buildings continues to rise. Buildings account for 20-40% of the total final energy consumption in developed economies [10] but this could be as high as 70% in developing countries [11]. This has led to a proliferation of building energy standards. A survey in 1994 [12] found 27 countries had mandatory energy standards (a further 11 had voluntary or mixed standards) among the 57 countries surveyed; this has risen to 40 countries (mandatory standards) and 21 (voluntary or mixed) in 2009 [13]. A further 11 countries had proposed new building energy standards. The growth in developing countries is particularly striking: a more recent survey [14] found over 60 developing countries now have mandatory or voluntary standards. Such standards invariably require performance benchmarks in the form of energy and/or climate indices.

An index to assess the climatic suitability of different U.S. climates for natural ventilation of commercial buildings was developed by Axley and Emmerich [15]. A computer tool based on this methodology is also available [16] for U.S. climates. Despite this, recent efforts to quantify the 'energy burden' of climates are relatively rare.

However, there are many recent efforts to develop indices to benchmark building energy needs. An overview of efforts in the EU is provided by Thomsen and Wittchen [17]. A simple energy index called Normalised Energy Use Index (NEUI) was developed for Brazilian buildings [18]. NEUI uses simulated building energy use and normalises it using a function dependent on outdoor temperature. Comparisons with a Brazilian building showed good agreement.

A key need in devising building energy indices is to include the so-called 'lifecycle energy needs' (energy use in construction to demolition, and energy embodied in buildings). In the face of increasing demands for low/zero energy buildings, the latter (embodied energy) could become an important part of the total energy used in buildings. This is not addressed by most of the current building energy assessment or rating methods. A methodology to develop a lifecycle energy index is proposed by Hernandez and Kenny [19].

A further confounding factor is the increasingly complicated nature of building energy use evaluation systems. A recent proposal [20] to develop a weighted energy index for buildings suggested 25 indicators in 6 categories ranging from heating/cooling load, equipment efficiency, embodied energy in building materials, operational and management functions, renewable energy and indoor climate and health.

2.3 The proposed CEI/BEI

The CEI/BEI developed by the IES Ltd is an attempt to quantify the energy burden on a building by outside air. It has four component loads: two sensible energy loads (heating and cooling) and two latent energy needs (humidification and dehumidification). The CEI is defined thus:

$$CEI = \text{Sum of (Sensible Cooling, Sensible Heating, Humidification, dehumidification)}.$$

It is expressed in kWh/yr for a given volume of air (in m³/hr). Table 1 presents the CEI values for 14 representative geographical locations from around the world.

[Table 1 approximately here]

The Building Energy Index (BEI) expresses the CEI in terms of energy need of a given building.

$$BEI = \frac{CEI}{OA \times FA}$$

where, BEI= Building Energy Index (kWh/yr/m²);

OA= Outside air intake (both infiltration and auxiliary ventilation (m³/hr);
FA = Floor area (m²)

3. Method

3.1 IES VE Platform

The Climate Energy Index (CEI) and Building Energy Index (BEI) have been implemented into IES' main dynamic thermal simulation software IES Virtual Environment (IES VE). This enables calculations of the CEI and BEI to be accomplished effectively and quickly. All the inputs required for generating the CEI are simply weather data of a particular location and building hours of use. IES VE provides a worldwide range of hourly weather data. A standard format of weather file – EnergyPlus Weather (EPW) is employed for this purpose. It is also possible to convert other formats to these formats using third party products.

Furthermore, the implementation of the CEI and BEI is accomplished through the IES VE-Navigator tools under 'Climate Index' session, which offer an easy to use workflow system, step-by-step guidance, reports, a built-in Quality Assurance system and analysis automation. The IES VE-Navigators share an integrated interface with VE-Gaia and VE-Pro and work in conjunction with these tools or can stand alone.

[Figure 1 approx. here]

3.2 Test protocols

In order to validate the CEI/BEI, we followed the following approach:

Compare the CEI against a previously developed and validated attempt to quantify the 'climatic burden';
Compare the BEI outputs against the output from a simple parametric building energy simulation tool.

The index chosen for the comparison of CEI is the Mahoney's Table [9]. A detail overview of the chart is presented in Appendix 1. We used DEROB-LTH [21] to compare the outputs from the BEI.

Ten types of buildings were simulated to derive their energy use. Appendix 2 shows the details of

these buildings. Since the energy use of these buildings is a function of the design assumptions, we simulated three types of constructions: 'GREAT,' 'GOOD' and 'POOR' buildings. Assumptions used for each of these types are given in Section 4.2.

4. Results

4.1 Validity of the Climate-Energy Index (CEI)

The CEI is directly comparable in its approach to Mahoney's Chart [9]. Mahoney's Chart combines Air temperature (AT), Relative Humidity (RH), Wind and precipitation data to gauge the necessity for pre-determined passive / low energy building responses to climate.

However, the purpose of Mahoney's Chart is to propose appropriate design strategies and therefore no attempt is made to combine the disparate quantification of climatic burden (in terms of heating, ventilation, rain protection, etc) into a single number. In order to make our comparison work we needed to convert Mahoney's Chart numbers into a single index.

We used the following approach to derive a single index out of the Mahoney's Chart. Mahoney's Chart has six indices to quantify the 'climatic burden' of a given climate:

- H1 – Ventilation essential
- H2 – Ventilation desirable
- H3 – Rain protection essential
- A1 – Thermal mass essential
- A2 – Outdoor activity possible
- A3 – Heating essential

Based on these indices, the Chart recommends design strategies in terms of the following passive design options:

- ventilation
- rain protection
- thermal mass
- heating

Our rationale for combining these indices into a single Mahoney's Chart number is based on the premise that all six indices cannot be of equal weight. Indices that are termed 'essential' need to have higher weighting than those that are termed 'desirable.' (for example, H1 and H2 are not of the same weight; H1 being an 'essential' criteria should have a higher weightage than H2 – a desirable criteria). For the purpose of our analysis, we created a modified Mahoney's Chart number (MC_m) by multiplying all of the 'essential' criteria by 2 and 'desirable' or 'possible' criteria by 1, and normalising these to derive a single number:

$$MC_m = \frac{\{(H_1 \times 2) + (H_2 \times 1) + (H_3 \times 2) + (A_1 \times 2) + (A_2 \times 1) + (A_3 \times 2)\}}{10}$$

Given the fact that the individual indices are quantifying the 'climatic burden' they could be added and our weighting enables the essential criteria to dominate the final result.

MC_m was compared with CEI (by simple regression) and the anomalies, if any, were examined against a bioclimatic chart to explain the 'severity' of the climatic load. For this purpose we chose the most widely used bioclimatic chart – Givoni's thermal comfort chart [22]. Givoni's Chart plots monthly maximum/minimum air temperature/relative humidity onto a modified psychrometric chart showing zones of influence of nine passive/active building design options.

Figure 2 shows a comparison of CEI with MC_m for 14 cities from around the world (see Table 1 for the cities). Weather data for our calculations were obtained from a source independent [23] of the one used for the calculation of CEI:

[Figure 2 approx. Here]

As can be seen from Figure 2 the match between the two indices is very poor. However, the situation improved dramatically when an outlier (in this case, Phoenix, USA) was removed (see Figure 3)

[Figure 3 approx. here]

The reason for the improvement in Figure 3 is the 'extreme' nature of the climate of Phoenix. Figure 4 plots the monthly weather data for Phoenix on Givoni's Bioclimatic chart. As can be seen from Figure 4, the monthly climatic conditions vary widely (from very hot, dry in July and August daytime to very cold and humid nights in December to February). Thus, any attempt to look at the 'annual' climatic burden will tend to gloss over the extreme variations in monthly climate requirements (i.e. the de-humidification need in the winter will be cancelled by the humidification need in the summer). This can be seen from a comparison of the annual humidification needs of Phoenix with a wetter climate (say, Glasgow) – 0.6 kWh/yr/m³/hr (Phoenix) vs. 0.36 kWh/yr/m³/hr (Glasgow), with the relative humidity of the former varying greatly across the year (Phoenix = from 22% in June to 51% in December and January) than the latter (Glasgow= from 74% in May to 86 in December and January). Similarly other 'mild' climates such Sydney, Australia (Figure 5) have less seasonality and therefore a more uniform 'climatic burden.'

The importance of humidity was underscored by a recent exercise to develop a climate suitability index in the U.S. The index developed by the National Institute of Standards and Technology (NIST) in the U.S. [16] found suitability of natural ventilation to increase the effectiveness of cooling is very dependent on the acceptable humidity range. If a dewpoint limit is used, the increase is significant for a dry climate such as Phoenix but much smaller for humid climates such as Miami [16]. While adaptive comfort standards such as the ASHRAE Standard 55 do not impose a limit on humidity when using the adaptive thermal comfort option, the necessity of limiting humidity for other reasons needs to be considered.

We therefore recommend the following:

1. CEI is a good indicator of the 'climatic burden' imposed on buildings by 'mild' external climates (i.e. climate that have a more predictable variation in their monthly climatic burden on buildings)

2. Its performance may be improved by examining any data anomaly (especially with respect to 'humidification' and/or 'de-humidification')
3. If point no. 2 does not adequately address CEI's performance in extreme climates (i.e. climates with wider monthly variations) perhaps a weighting factor could be introduced to either increase or decrease the importance of latent energy need (i.e. humidification or de-humidification).

[Figure 4 approx. here]

[Figure 5 approx. here]

4.2 Validity of the BEI

The validation of BEI involved simulating the energy performance of the 10 types of buildings

ranging from single family residential buildings to very large office and institutional buildings (shown in Appendix 2), each building under three construction assumptions:

1. Buildings designed to meet the best practices in the developed world (i.e. assuming an indoor condition where the predicted mean comfort vote – PMV lies within -0.50 to +1.00). This category of buildings is called 'GREAT' buildings;
2. Buildings designed for basic code standards as applicable in most developed countries (e.g. designs fulfilling the adaptive comfort standards – ASHRAE 55 -2004 [24] and is defined by ASHRAE 55: 2004, Figure 5.3 with 80% acceptability. Such an approach is also allowed in many 'sustainable building' assessment methodologies, for example LEED IEQ 7.1 [25] and Green Star IEQ 9). This category of buildings is called 'GOOD' buildings;
3. Buildings designed for basic standards currently prevalent in the developing world (i.e. within an internal PMV of ± 1.5). This category of buildings is called 'POOR' buildings.

Our approach to validate the BEI was as follows:

1. Compare BEI of the ten different types of buildings shown in Appendix 2 for each of the 14 cities, against building energy performance for 'Poor' and 'Great' buildings
2. Attempt to explain variations
3. Compare all of the BEI values with energy performance estimated by a generic building simulation software outputs

The reason for selecting 'Poor' and 'Great' buildings while dropping 'Good' buildings is to account for the fact that improving building standards everywhere (as discussed in Section 2.2) are progressively mandating such buildings to be the norm. However, the existing building stock, especially in the developing world continues to be 'Poor.' At the other end of the spectrum, the current emphasis on third party accreditation of buildings for their 'sustainability' credentials (such as BREEAM, LEED, etc)

is invariably pushing the energy performance over and above the current norm; thus 'Great' in our classification. It is to be acknowledged that such efforts are currently 'aspirational' and not yet mandatory in many countries. Nevertheless our comparison of BEI against 'Great' and 'Poor' could show the applicability of the index to both standard and aspirational building design practices.

For the purposes of Task 3 above, we used a parametric building energy simulation software called DEROB-LTH developed by the Lund University, Sweden [21]. DEROB-LTH is capable of simulating the indoor thermal comfort and building cooling/heating energy needs. It needs following climatic inputs:

- Outdoor average daily maximum and minimum air temperature;
- Outdoor average daily maximum and minimum relative humidity;
- Average daily cloud cover (or total global radiation)
- Average monthly rainfall

Figure 6a shows the comparison of energy performance vs. BEI for 'POOR' buildings in the 14 climatic locations selected for the study. As is to be expected the predictive ability of the BEI in terms of a building's energy needs is rather poor ($R^2 = 0.403$). BEI's predictive ability improved significantly in the case of 'GREAT' buildings (Figure 6b). The case improves even further when energy performance data for hot, humid locations (Singapore, Miami and Bangkok) for one of the more outlandish designs (a building called M8 – mostly glazed and a design more suited to temperate conditions) is removed (Figure 6c). This is to be expected, given the low likelihood of all design types being constructed in all selected climatic locations. It is therefore safe to say that the BEI index is a good predictor of the likely energy performance of buildings that fulfils the current best practices in the developed world. In this sense, the BEI therefore fulfils its intended purpose (i.e. a simple and universal predictor of building energy performance of 'sustainable' buildings).

[Figure 6 approx. here]

4.3 Robustness of the BEI

As indicated in the previous section, we compared the BEI values for all 10 buildings in all 14 climatic locations. The rationale for selecting these buildings is that these are considered 'sustainable' on account of their assessed scores under a building sustainable assessment methodology such as the BREEAM. It is highly unlikely that all of these buildings will ever be built in all of the selected locations, given the wide variations in local climate. For example, heavily glazed and un-shaded buildings are highly unlikely to be considered 'sustainable' in a warm, humid climatic context. We therefore removed the unlikely combinations (mainly, those in the hot, humid cities of Miami, Singapore and Bangkok). Figure 7 shows the BEI vs. Energy consumption data for 'Great' buildings in all cities excluding the 'hot, humid' cities (i.e. excl. Miami, Bangkok and Singapore). As can be seen from Figure 7, the predictive ability of BEI is improved even more.

[Figure 7 approx. here]

A possible explanation for this improved predictive ability is the pooled (sensible plus latent) nature of the building energy data used for the exercise. The removal of hot, humid cities from the mix reduces the importance of latent energy needs, thus the improved performance. Such a hypothesis is supported by Figure 8. Figure 8a shows the relationship between BEI and sensible building energy need (sensible heating or cooling) while Figure 8b shows the BEI vs. Latent building energy needs (humidification and/or dehumidification). The improved R^2 values for the former indicate that the BEI is a better predictor of sensible energy needs. This again points to the need for a separate (or a weighted) approach to the problem of moisture, much as the discussion on CEI previously indicated.

[Figure 8 approx. here]

We also analysed the predictive ability of the BEI index of the building energy performance of 'POOR' buildings. Given the global ambitions of the CEI/BEI indices, such a robustness test is important. Most buildings (especially in the developing world) are yet to reach the superior indoor

thermal environmental standards demanded by the best practice regimes currently in operation. In other words, a vast majority of buildings designed and built in the current context remain within our 'POOR' category and therefore, professionals from around the world will find it of immense value if the BEI index could predict the energy performance of these buildings.

Figure 9 shows a comparison of BEI against building energy performance for all buildings in all cities excluding the three hot, humid cities (Miami, Bangkok and Singapore). It is clear that the predictive ability of the BEI is very good even in the case of 'POOR' buildings. (R^2 for 'POOR' and 'GREAT' buildings were 0.9077 and 0.9321 respectively). This further reinforces our earlier conclusion that the BEI index is a very good predictor of the building energy performance, even if the buildings are constructed to a 'POOR' thermal comfort standard.

[Figure 9 approx. here]

5. Implications and Conclusions

In this paper we tested the validity of the Climate Energy Index (CEI) and the Building Energy Index (BEI) developed by IES Ltd. We compared the efficacy of the CEI against previously developed and tested climate quantification indices (in this case, the Mahoney's chart). We also analysed the performance of the BEI against three categories of buildings (those conforming to best practice standards in the developed world; basic standards in the developed world and those not conforming to current thermal comfort regulations) for 10 different building types in 14 different cities from around the world. Furthermore, we performed robustness tests in terms of climate and building sub-types as well as latent and sensible energy needs to better understand the performance of the BEI.

Based on our work we could conclude as following:

1. CEI has a good match with previous attempts at quantifying the 'climate burden' on buildings with one exception: Phoenix

2. The outlier case may be explained by the unusually low humidification energy need for Phoenix and/or the equal weighting given to both the 'sensible' and 'latent' energy loads of a given climate.
3. The BEI seem able to predict well the performance of 'Great' buildings than 'Poor' buildings.
4. The performance of 'Poor' buildings improves dramatically if 'hot, humid' climates are excluded (i.e. Miami, Singapore and Bangkok cases)

Finding (4) above indicates a possible strategy to improve future efforts to develop indices to quantify the climatic burden of climates dominated by dehumidification and is discussed below.

5.1 Future directions

The prototype Index has the potential to form the basis of a unique design tool that will allow the comparison of designs worldwide in a simple and independent fashion. As an easy to develop index, the BEI (and the CEI) has the potential to provide a common method to compare the energy performance of buildings (and different design strategies) in different climatic regions.

Given the global aspirations of the CEI/BEI approaches, it is necessary to enhance the predictive ability of the BEI in hot, humid climates as well. Based on our results (see Finding 4 above) such improvements might involve developing different weighting factors for latent and sensible energy needs, depending on the climatic conditions. It might also be prudent to increase the 'value' (i.e. weightage) of passive design approaches (i.e. ventilation, thermal mass and perhaps solar radiation) in the building category we have termed as 'POOR.'

Acknowledgements

Funding for this study was provided by the CIC-Start Online Project (<http://www.cicstart.org/>), funded by the European Regional Development Fund (ERDF) and the Scottish Government.

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Appendix 1 – Mahoney’s Chart: an example for Singapore

Indicator totals from data sheet					
H1	H2	H3	A1	A2	A3
12	0	2	0	0	0

Singapore
Latitude 1°N

General recommendations

Layout

			0–10			X	Orientation north and south (long axis east–west)
			11–12		5–12		
					0–4		Compact courtyard planning

Spacing

11–12						X	Open spacing for breeze penetration
2–10							As above, but protection from hot and cold wind
0–1							Compact layout of estates

Air movement

3-12							
1-2			0-5			X	Rooms single banked, permanent provision for air movement
			6-12				Rooms double banked, temporary provision for air movement
0	2-12						
	0-1						No air movement requirement

Openings

			0–1		0	X	Large openings, 40–80%
			11–12		0–1		Very small openings, 10–20%
Any other conditions							Medium openings, 20–40%

Walls

			0–2			X	Light walls, short time-lag
			3–12				Heavy external and internal walls

Roofs

			0–5			X	Light, insulated roofs
			6–12				Heavy roofs, over 8h time-lag

Outdoor sleeping

				2–12			Space for outdoor sleeping required
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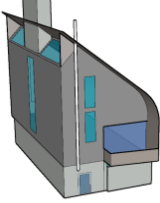

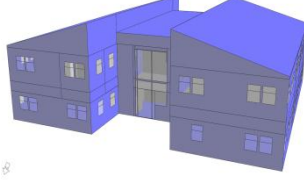
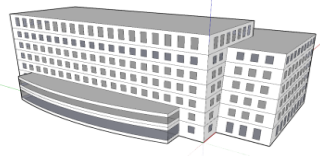
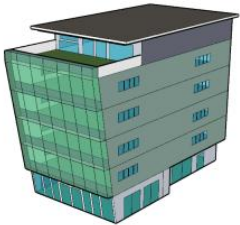
Rain protection


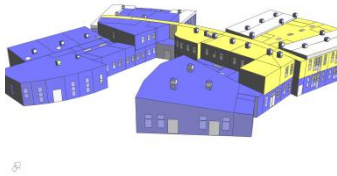
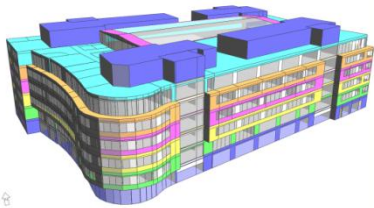
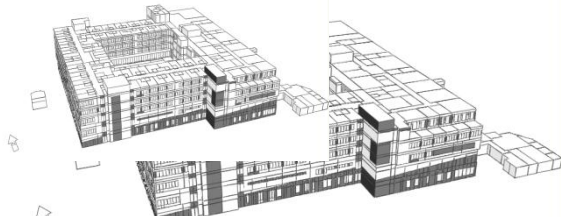
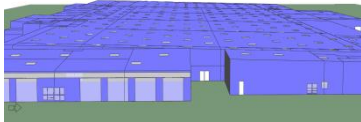
		3–12					Protection from heavy rain necessary
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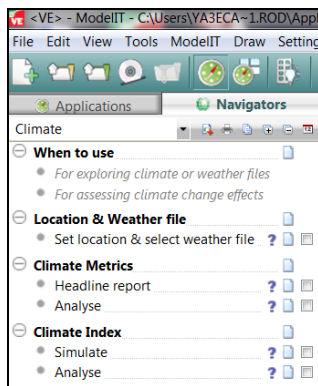
Detailed recommendations

Size of opening						
			0–1		0	<div>X</div> Large openings, 40–80%
					1–12	<div></div> Medium openings, 25–40%
			2–5			
			6–10			<div></div> Small openings, 15–25%
			11–12		0–3	<div></div> Very small openings, 10–20%
					4–12	<div></div> Medium openings, 25–40%
Position of openings						
3–12						<div>X</div> In north and south walls at body height on windward side
1–2			0–5			
			6–12			<div></div> As above, openings also in internal walls
0	2–12					
Protection of openings						
					0–2	<div>X</div> Exclude direct sunlight
		2–12				<div>X</div> Provide protection from rain
Walls and floors						
			0–2			<div>X</div> Light, low thermal capacity
			3–12			<div></div> Heavy, over 8h time-lag
Roofs						
10–12			0–2			<div>X</div> Light, reflective surface, cavity
			3–12			<div></div> Light, well insulated
0–9			0–5	<div></div> Heavy, over 8h time-lag		
			6–12			
External features						
				1–12		<div></div> Space for outdoor sleeping
		1–12				<div>X</div> Adequate rainwater drainage

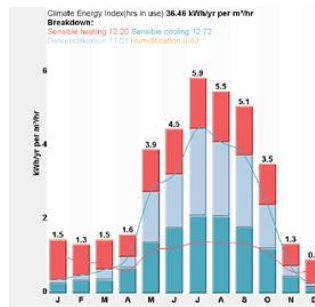
Appendix 2 – Selected buildings used for the BEI exercise

Ref	Model Name	Model image	Building Type	Floor Area (m ²)	Volume (m ³)	No. of Rooms
1	BRE		Residential	309	1758	5
2	Newhouse		Residential	332	818	15
3	Helix		Small office	864	6671	46
4	M4		Large office	17195	66785	7
5	M8		Lab/Research	2089	7558	6

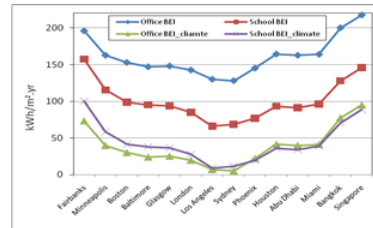
6	Walberton		Small school	2195	7101	55
7	Featherstone		Large school	4305	15708	130
8	Hastings		College	39516	87755	764
9	Beaumont			25603	90226	
10	Walmart		Retail	28641	127947	237



(a) Implementation of CEI and BEI



(b) Example of CEI output



(c) Example of BEI output*

* The BEI output shown here is yet to be fully implemented in the IES-VE platform

Figure 1: Implementation of BEI and CEI in the IES Virtual Environment software

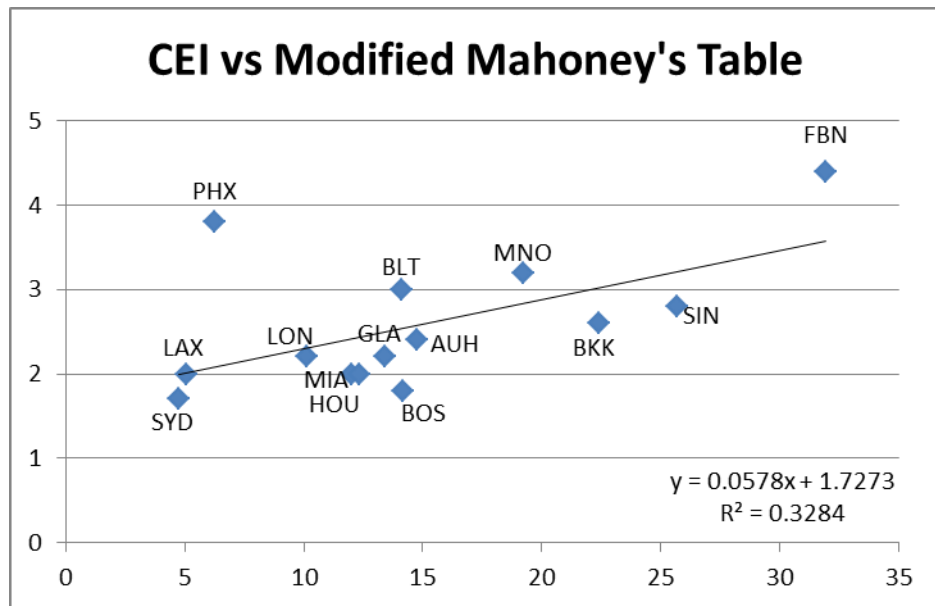


Figure 2: Comparison of 'climate burden' imposed by 14 cities from around the world

Key:

SYD – Sydney, Australia
 LAX – Los Angeles, USA
 PHX – Phoenix, USA
 LON – London, UK
 MIA – Miami, USA
 HOU – Houston, USA
 GLA – Glasgow, UK
 BLT – Baltimore,, USA
 BOS – Boston, USA
 AUH – Abu Dhabi, UAE
 BKK – Bangkok, Thailand
 SIN – Singapore
 FBN – Fairbanks, USA
 MNO – Minneapolis, USA

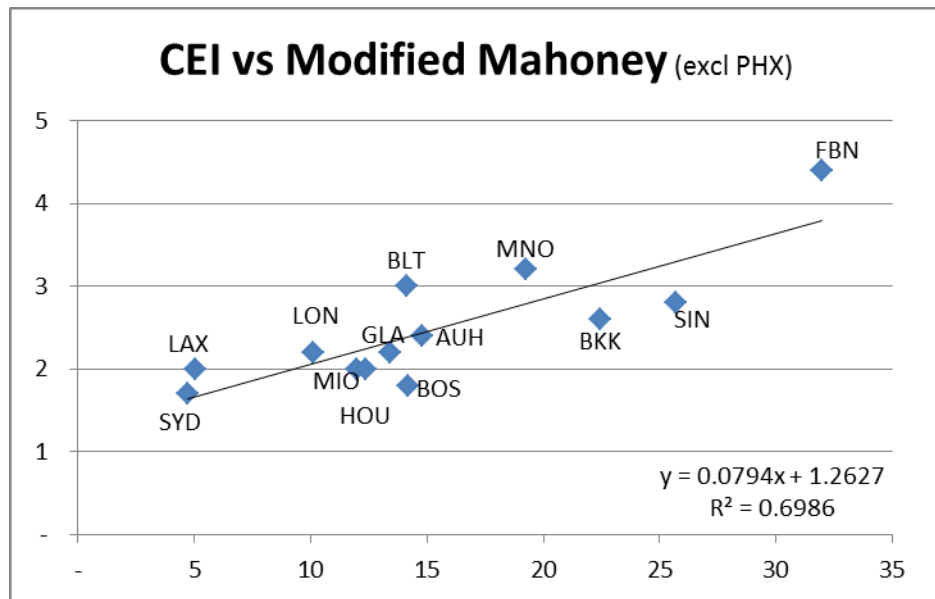


Figure 3: Improved predictive ability of CEI

(Please refer to Figure 2 for Key)

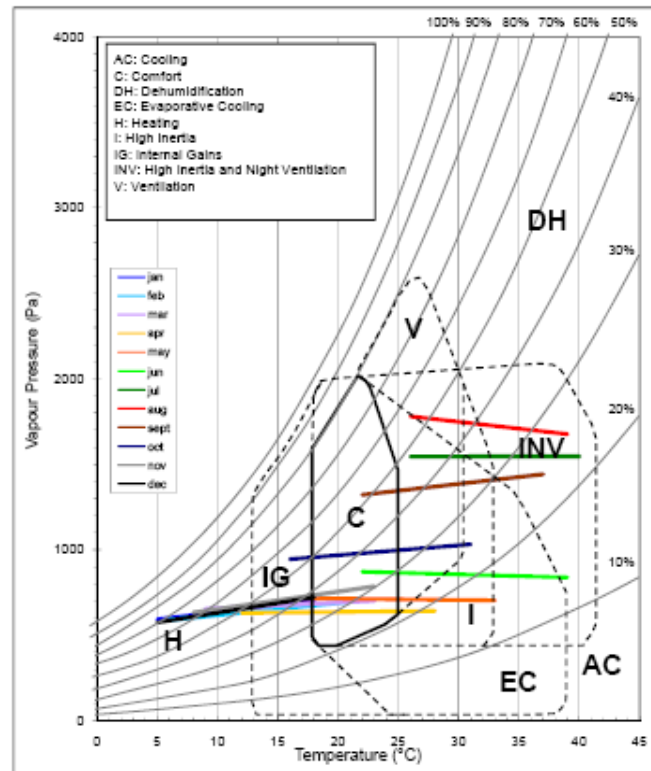


Figure 4: Bioclimatic need in an 'extreme' (Phoenix, USA) climate

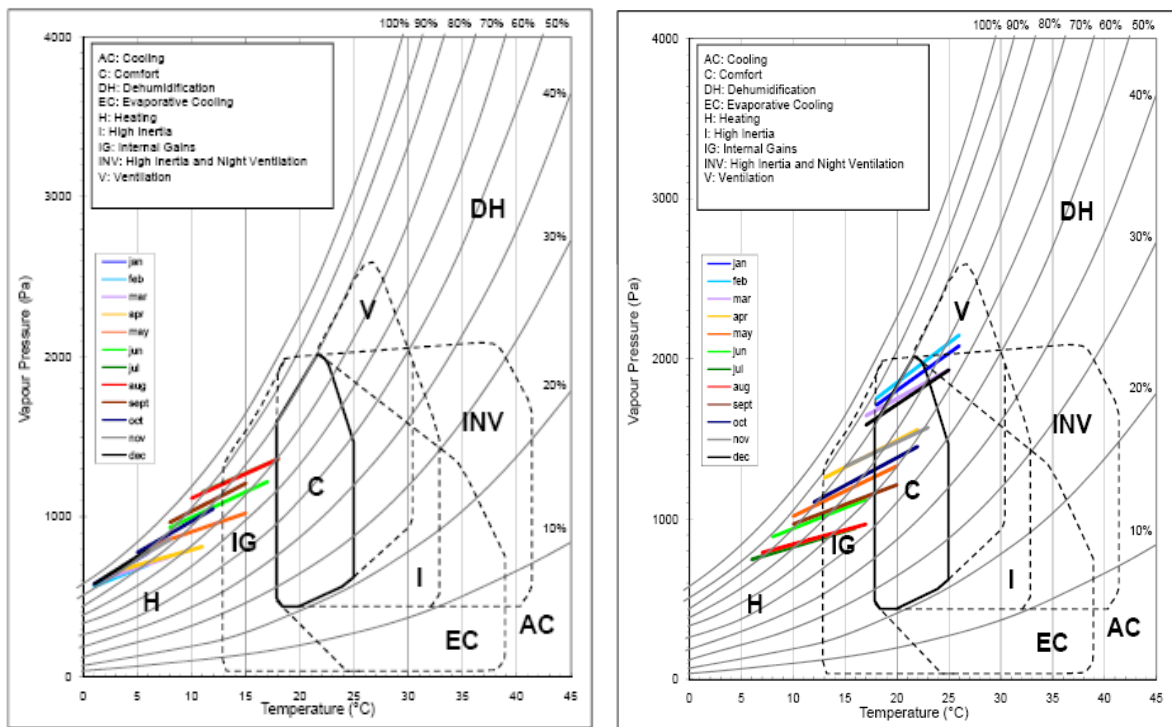


Figure 5: Bioclimatic need in more uniform climates (Glasgow on left and Sydney on right)

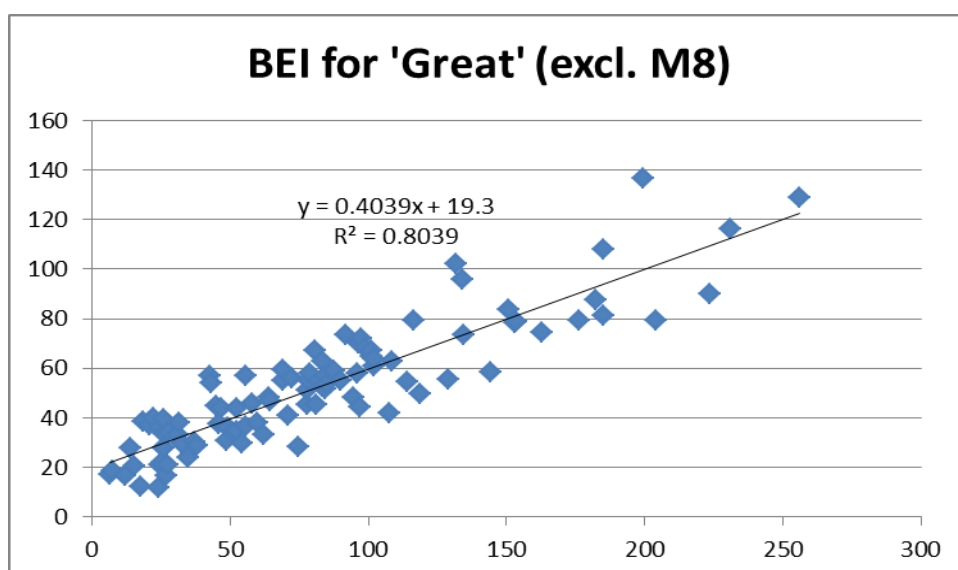
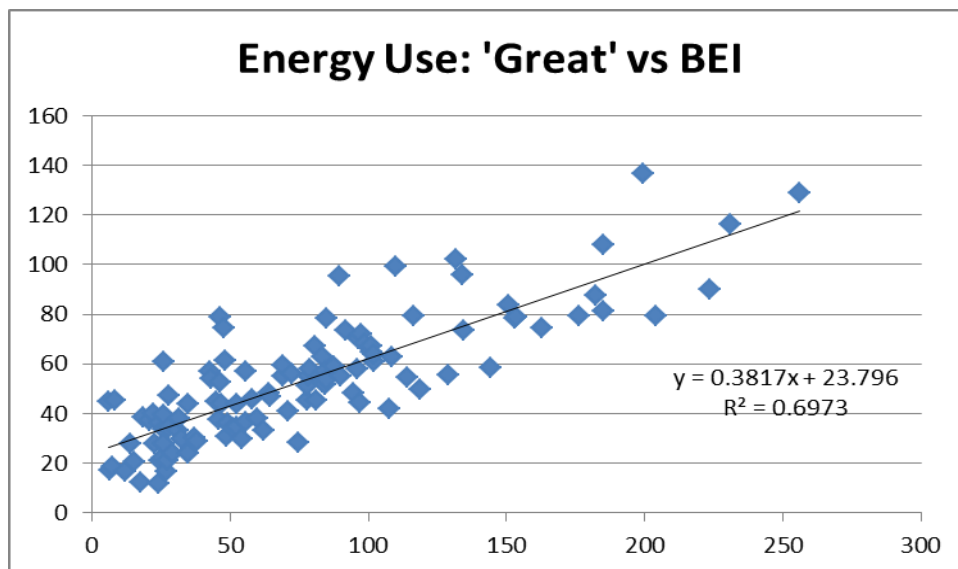
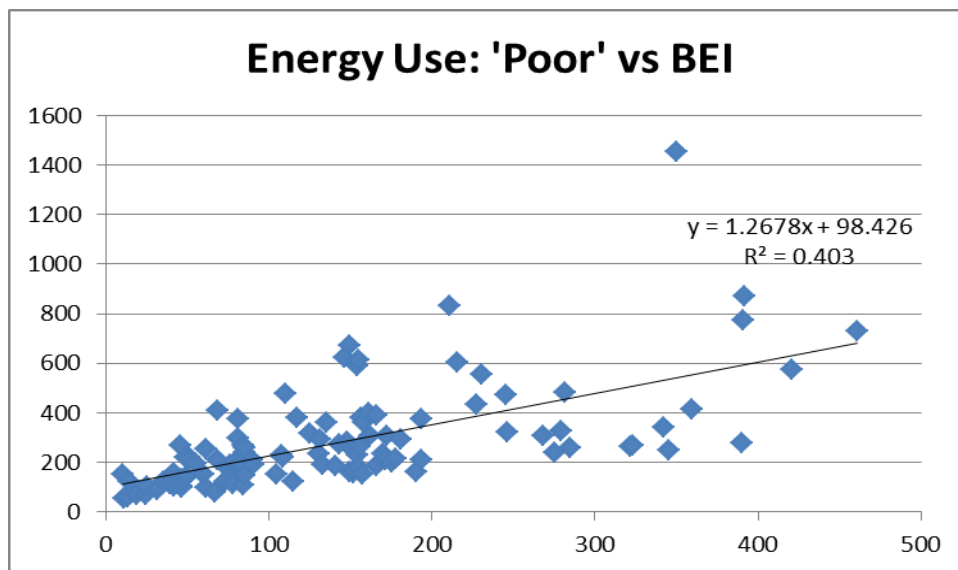


Figure 6: BEI Performance validation

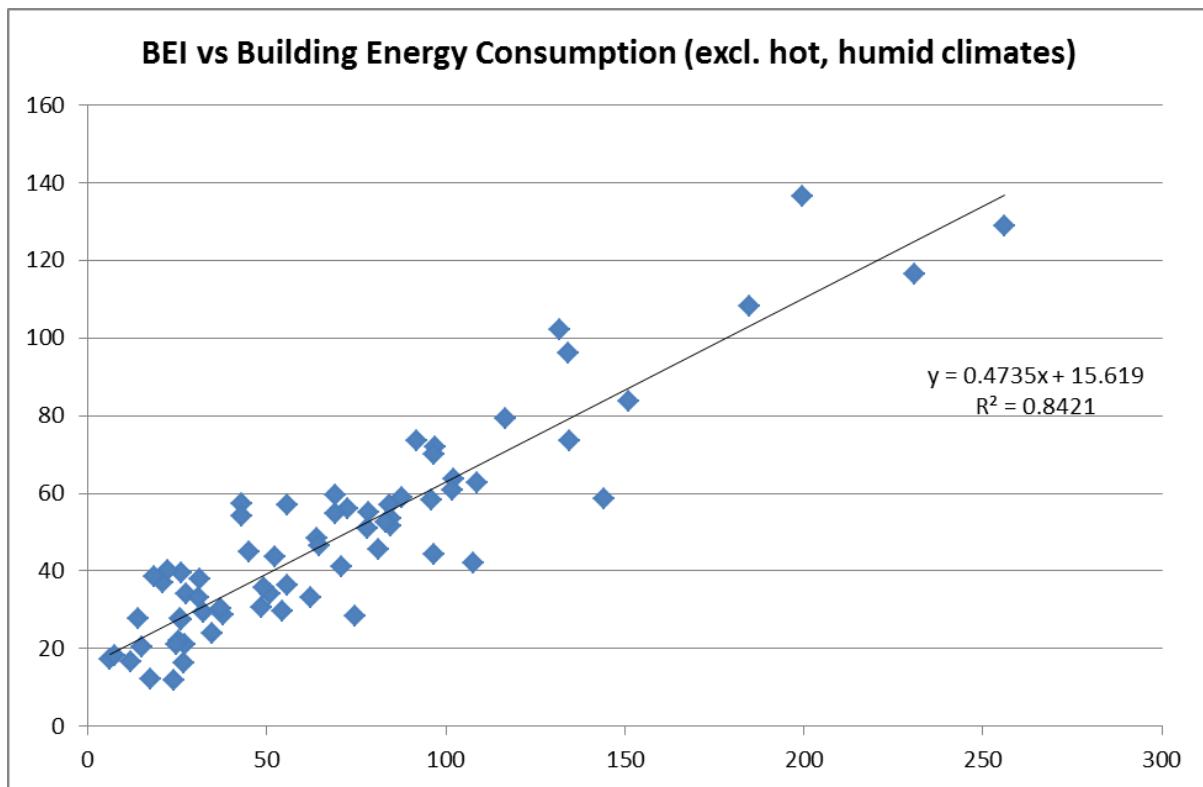


Figure 7: Building energy consumption and BEI excluding hot-humid cities

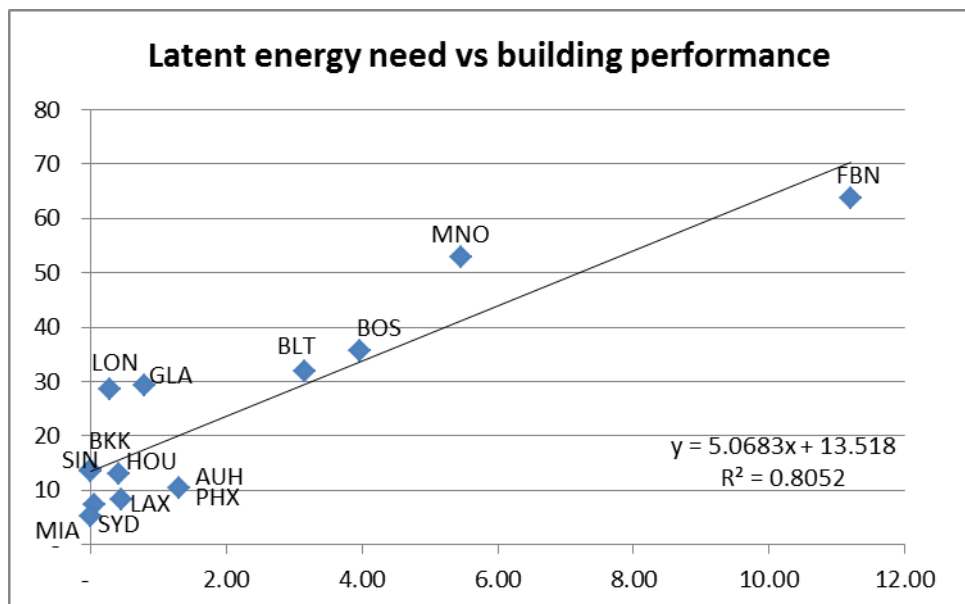
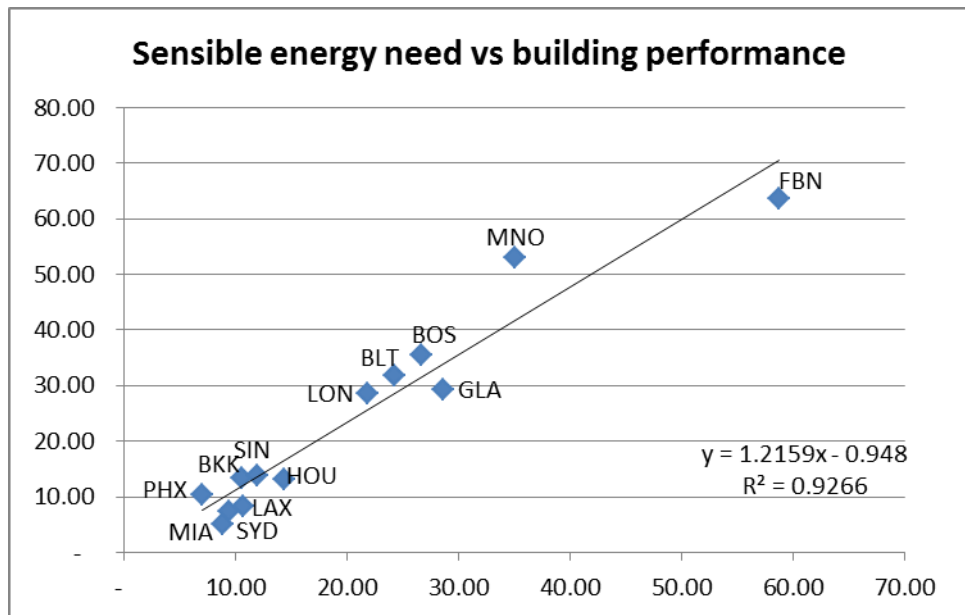


Figure 8: BEI and the sensible/latent building energy needs

(Please refer to Figure 2 for Key)

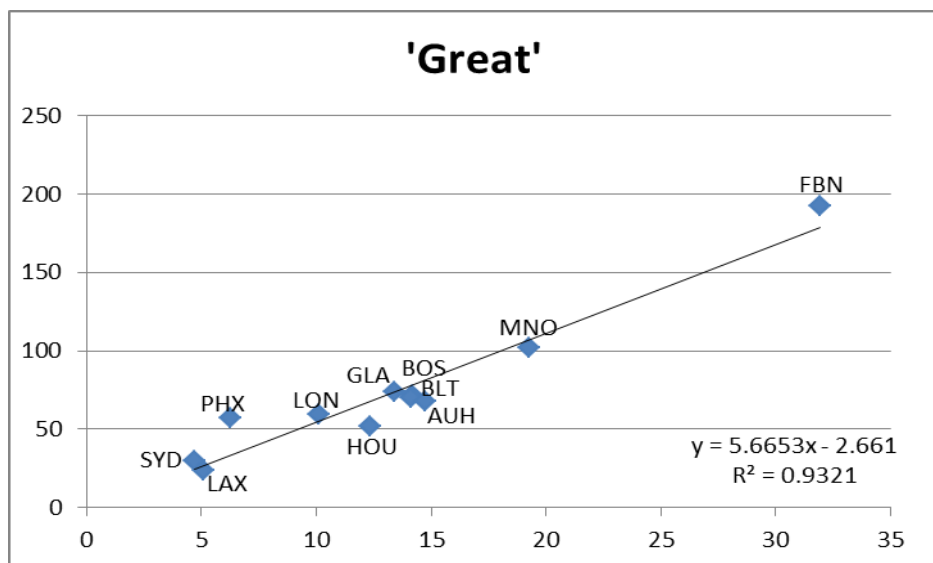
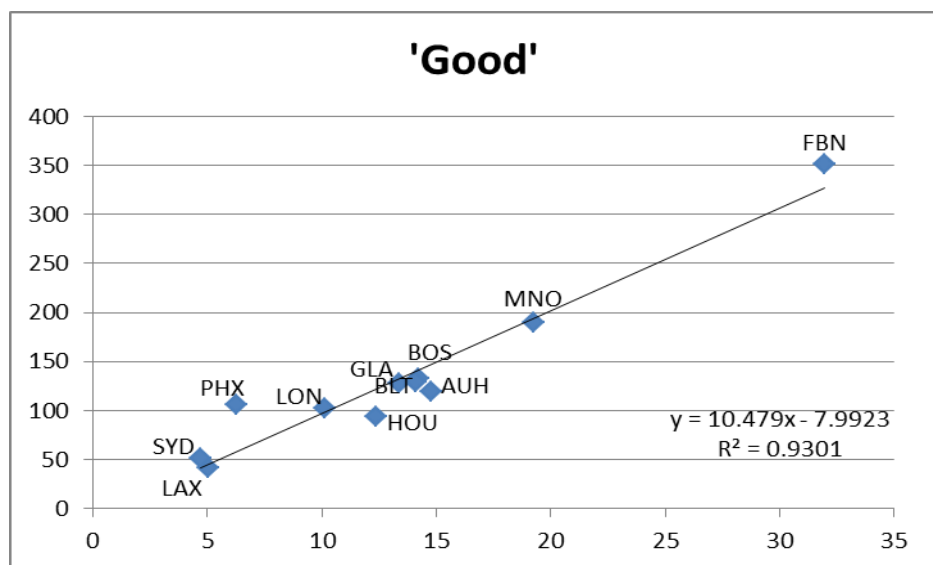
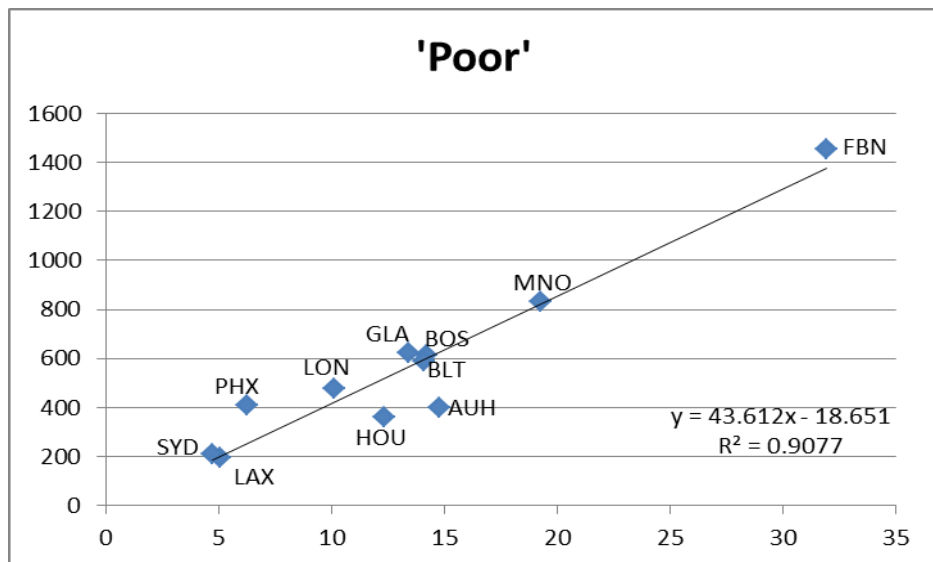


Figure 9: BEI performance in all climates excluding the 'hot, humid' cities
(Please refer to Figure 2 for Key)

